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Progress Report for the Space Physics Theory Group at the University of New Hampshire for the period March 1993 - April 1994

prepared April 22, 1994

The following is a summary of the scientific work accomplished under NASA grant NAG5 - 1479, from the Space Physics Theory Program to the University of New Hampshire.

CORONAL MASS EJECTIONS, AND RELATED PHENOMENA

The ejection of matter into interplanetary space by coronal mass ejections has long confronted theorists with the apparent paradox of stretching magnetic field lines while releasing magnetic energy. T.G. Forbes and P.A. Isenberg believe they have finally resolved this paradox, at least within the framework of two-dimensional MHD models. Their work builds upon earlier work by Van Tend and Kuperus and others who pointed the way towards a possible resolution by developing a simple model based on the eruption of a magnetic flux rope. In the Van Tend & Kuperus model, the flux rope erupts because the balance between magnetic compression and tension cannot be maintained as the photospheric field evolves in time. However, their model was based on circuit concepts which are difficult to justify in the solar atmosphere, so their model was more or less ignored for several years. Forbes, and more recently Isenberg, have reformulated Van Tend & Kuperus' original idea within the framework of MHD and found that it is still a viable principle. However, the quantitative aspects of the MHD model are quite different than those of the original Van Tend & Kuperus circuit model, and energetic eruptions are far more difficult to achieve than the circuit model implied.

The reformulation has proceeded in stages which are only now reaching full fruition. During the last 12 months Isenberg, Forbes, and Priest published an article which shows how to incorporate Parker's MHD solution for a flux rope in free space into the more complicated configurations required to explain coronal mass ejections. Subsequently, Forbes, Priest, and Isenberg used these results, and the principals of variational calculus, to find the boundary condition on the photospheric magnetic field which maximizes the energy released during a coronal mass ejection.

The new boundary condition represents a breakthrough in the effort to model coronal mass ejections using flux ropes, because previous choices for the photospheric boundary conditions either led to no ideal-MHD eruption or to eruptions which released an insignificant amount of energy. The new boundary condition, which more nearly resembles actual conditions on the Sun, releases 20% of the free magnetic energy stored in the corona. This is more than enough to explain the observations. The new boundary condition is also ideally suited for numerical simulations of coronal mass ejections and associated phenomena such as eruptive flares and prominence eruptions.

PARAMETRIC INSTABILITIES OF ALFVÉN WAVES

Even though parallel-propagating circularly-polarized Alfvén waves are an exact solution to the MHD equations, they were shown by Galeev and Oraevskii to be unstable to density perturbations. The resulting "parametric" instabilities may be a means of transferring energy from the waves to the plasma particles, and they may be part of the evolution of a field of Alfvén waves to the turbulent state seen in the solar wind. During the past year we have investigated several aspects of these parametric instabilities.

Graduate student Venku Jayanti (who is supported by another source) and J.V. Hollweg noted that even though these waves have been of interest for more than three decades, there has been very little analytical work on them. They pointed out that some "new" instabilities, which had been previously reported by other workers, were in fact non-existent, because a proper Floquet analysis of the equations had not been done. In a separate paper, they showed that the dispersion relation in the low-frequency MHD limit is strongly dependent on the plasma β, and that a proper analysis of the dispersion relation requires distinguishing four ranges of β. They showed that the familiar decay instability exists in only one of these ranges. If $\beta \approx 1$, or if $\beta \gtrsim 1$, then the instability is really a beat instability, which does not readily generate the backward-going Alfvén waves which are invoked as part of the turbulent cascade. Since $\beta \approx 1$ in the solar wind much of the time, we conclude that one can not simply use the familiar decay instability to generate the observed turbulent state. In a further study, Hollweg extended the analytical work to include

dispersion which arises from ion cyclotron effects. In this case a modulational instability is introduced. There is also another new instability which has sometimes been called the beat instability, but it has usually been ignored because it was wrongly thought to exist only in a narrow frequency band and to have a small growth rate. However, Hollweg shows that the beat instability can be the most important instability if $\beta \gtrsim 1$. He also shows how the beat and the decay instabilities are related, and how they have sometimes been confused in the past by other workers. These papers have either been published or accepted by the Journal of Geophysical Research.

Jayanti and Hollweg have also examined the effects of streaming He^{++} on the parametric instabilities. Using a fluid model, they find that there are four new instabilities which exist in virtue of the streaming He^{++}. Three of these exist at high frequencies and wavenumbers. They may compete with the familiar decay instability, in the sense that their growth rates may be comparable to or larger than the decay growth rate. This makes these instabilities interesting, since they may be a means of taking energy out of the Alfvén waves and dumping it into the He^{++}. But a full kinetic treatment, which is under development as part of Mr. Jayanti's thesis, is needed to properly assess this intriguing possibility.

Another approach to studying parametric instabilities is to use numerical simulations. We have taken the approach of using a hybrid code, so that we can study kinetic effects at the same time. A one-dimensional hybrid code with a spectral field solver, particle ions, and fluid electrons, has been developed by B. Vasquez, and used to follow the instability and subsequent evolution of low (< ion cyclotron) frequency wavetrains propagating parallel to a background magnetic field. A previous hybrid simulation study by Terasawa et al. (JGR, 4171, 91, 1986) had considered only a narrow parameter range; they concluded that ion kinetics does not qualitatively change the evolution expected from fluid theory. Vasquez considered a wider parameter space, and unanticipated results were revealed which lead to the conclusion that ion kinetics alter wave evolution in a significant manner which cannot be explained with a simple modification of the fluid theory. The simulation results show that moderate amplitude ($\delta B/B < 1/2$) wavetrains give parametric instabilities and saturated states which differ completely from what is expected on the basis of fluid theory. This is most clearly seen when $\beta > 1$. The simulation shows that instability exists for wavenumbers both below and above that of the initial, left-handed wavetrain. For corresponding parameters, the fluid theory gives only a narrow range of instability above the pump wavenumber where the decay and beat instabilities occur. In the simulations, wave energy cascades to smaller wavenumbers and into a greater amount of forward- than backward- going waves. In contrast, in fluid theory energy by decay goes mostly to backward waves of smaller wavenumber and by beat goes mostly to forward waves of larger

wavenumber. Neither fluid instability explains the simulation results. The instability saturates by heating the ions, and does not generate harmonics of the initially unstable wavenumbers as would be expected for fluid ions. Some solar wind turbulence models now invoke fluid-like wave decay as a possible explanation for the observed decrease of cross helicity with distance from the Sun. Such models are suspect because the energy deposited in backward-going waves, which causes the decrease, depends critically on ion kinetics.

Currently, these results are being arranged for publication by Vasquez in the Journal of Geophysical Research. Future simulations and analyses will concentrate on how to incorporate in a phenomenological manner the behavior of parametric instabilities and ion kinetics into a solar wind model. And future work will incorporate the He^{++} particles being examined analytically by Jayanti and Hollweg.

PICKUP IONS IN THE SOLAR WIND

Our current pickup ion work has been largely motivated by the exciting new observations of these ions at the Ulysses spacecraft. The SWICS instrumenters have reported surprisingly large decreases in the flux of pickup He^+ over periods of months during the in-ecliptic portion of the mission. The Sun was particularly active during this time, suggesting that the decreases are due to long-term depletion of inflowing neutral helium following increases in the ionization rate. Isenberg and Lee have modeled the pickup helium decreases to be expected from increased photoionization, but have determined that this process is insufficient to explain the observations. We are currently investigating a model of pickup helium response to shock-related ionization increases, to see if the many shocks emitted by the Sun during early 1991 could be responsible for the flux decreases.

Isenberg has also joined with E. J. Smith and co-workers to interpret the Ulysses observations of pickup-proton-generated waves. These enhancements in the wave power at frequencies above the proton gyrofrequency (in the spacecraft reference frame) were predicted by Lee and Ip (JGR, 92, 11041, 1987) as the consequence of the pitch-angle scattering of newly picked-up protons to isotropy. These waves are not as prevalent as originally thought, but the enhancements that are seen are well explained by the theory. This work has been submitted to the Journal of Geophysical Research.

Isenberg and Lee have continued their collaboration with L. F. Burlaga and co-workers in analyzing the Voyager observations of pressure-balanced structures in the outer heliosphere. Earlier analyses of structures at 20 AU were unable to distinguish the effects of interstellar pickup protons from the equivalent pressure expected from solar wind electrons. However, at 40 AU, solar wind protons and electrons are far too cold to provide the

necessary pressure to balance the magnetic field variations in these structures, and this function appears to be completely taken over by the interstellar pickup protons. Such a conclusion implies pickup densities and temperatures which are consistent with the currently accepted values. This work has been submitted to the Journal of Geophysical Research.

Related to pickup ions is the behavior of reflected ions downstream of quasi-perpendicular supercritical shocks. M.A. Lee has nearly finished a theory of the relaxation, or thermalization, of these ions, which accounts for their residual temperature anisotropy and streaming, and the accompanying excitation of left-hand polarized proton-cyclotron waves just below the proton gyrofrequency. The theory is in excellent agreement with the observations of Sckopke et al. (JGR, 95, 6337, 1990) at Earth's bow shock. A paper with S.P. Gary in the Journal of Geophysical Research shows that this relaxation readily accounts for the observed correlation between the temperature anisotropy and plasma-β. This summer, in collaboration with S. Fuselier and W. Schmidt, we plan to include in the theory wave excitation by solar wind helium, which is substantial since all the helium appears downstream as a ring-beam distribution gyrating about the transmitted protons.

Finally, Isenberg is providing a review of work on interstellar pickup ions to be included in the U.S. National Report to the IUGG.

COSMIC RAYS IN THE OUTER HELIOSPHERE

As part of our contribution to "Cosmic Winds and the Heliosphere", M.A. Lee presented new analytical perturbation calculations describing the deceleration and heating of the solar wind by galactic cosmic rays and the cosmic ray anomalous component (presumed to be accelerated at the solar wind termination shock), and by the pickup of freshly ionized interstellar hydrogen and helium. The calculations also describe the weakening of the shock transition due to these particles, and the shift in its location. In the heliosphere these effects are generally $\leq$ 10%, with the exception of the dominant contribution of interstellar pickup ions to the solar wind pressure in the outer heliosphere.

Lee and former graduate student Bonnie Kwiatkowski (who was supported by another grant) developed a solution of the cosmic ray transport equation as an expansion in inverse powers of the spatial diffusion coefficient, which is useful for describing the time-dependent modulation of cosmic rays with energies greater than about 1 GeV/nucleon. We are in the process of writing up the successful application of the theory to Forbush decreases due to propagating interplanetary shock waves. We are also currently working on including drift transport in the theory and applying the results to describe the solar-magnetic-cycle modulation of cosmic rays.

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PERSONNEL MATTERS

We are pleased to report that the funds from this grant have enabled us to augment our efforts by hiring a postdoctoral research associate. We are fortunate in having had Dr. Bernard Vasquez join us in June 1993.

We are also pleased to report that Prof. Phillip Isenberg is in the process of being promoted from Research Assistant Professor to Research Associate Professor. UNH continues to recognize the quality of the members of this group, and to reward them accordingly.